Citation for published version:
Madhoushi, M & Ansell, M 2017, 'Effect of glue-line thickness on pull-out behavior of glued-in GFRP rods in LVL: Finite element analysis', Polymer Testing, vol. 62, pp. 196-202.

Publication date:
2017

Document Version
Peer reviewed version

Effect of glue-line thickness on pull-out behavior of glued-in GFRP rods in LVL: Finite element analysis

Mehrab Madhoushi [a], Martin P. Ansell [b]

[a] Department of Wood Engineering and Technology, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran.

[b] Department of Mechanical Engineering, University of Bath, Bath, UK

***** Corresponding author: Tel: +98-17-32427050, Fax: +98-17-32427176.

E-mail address: madhoushi@gau.ac.ir, mmadhoushi@hotmail.com(Mehrab Madhoushi)

ORCID ID: orcid.org/0000-0001-6845-2749

Effect of glue-line thickness on pull-out behavior of glued-in GFRP rods in LVL: Finite element analysis

Abstract

This paper uses finite element analysis (FEA) to verify the results of previous experimental works conducted on the effect of glue-line thickness and rate of loading on pull-out behavior of glued-in GFRP rods in LVL. For this purpose, the materials were considered as orthotropic for the timber and the GFRP rod, and isotropic for epoxy resin. To determine the effects of thickness on pull-out, four glue-lines namely 0.5, 1, 2 and 4 mm were modelled. To examine the effects of rate of loading, three glue-lines 0.5, 2 and 4 mm were modelled with different values of modulus of elasticity selected for the resin to simulate higher and lower rates of loading. Results showed that with an increasing thickness of glue-line, the concentration of Z-direction stresses declines across the glue-line thickness from the rod-adhesive interface towards the adhesive-timber interface and the magnitude of shear stresses, τ_{XZ} , increases to a maximum within the glue-line in a zone about 20-30% into the resin layer and this is seen for all glue-line thicknesses. Also, by changing values of elastic modulus for the resin in the FE model to simulate rate of loading, it was shown that thicker glue-lines are more sensitive to loading rate.

Key words: Epoxides, Wood and wood composites, Finite element analysis, GFRP, Glued-in rods, Glue-line thickness.

1. Introduction

Traditional timber connections may not be the preferred choice of connection system for heavy timber structures. Hence, timber structures require improved connections and more reliable products than the traditional timber connection systems based on fasteners such as nails, bolts, screws and dowels [1]. In Europe, this has led to the introduction of new types of timber connections such as glued-in bolts or rods through the EU GIROD (European Glued-in Rods) project which involved several European countries and aimed to draft an acceptable standard for joints based on glued-in rods in the context of Eurocode 5 [2]. Utilization of these new joints could remove some of the disadvantages associated with traditional joints, e.g. long manufacturing times, high labour cost, heavy joints and corrosion problems. Bonded in connections have advantages, for instance high stiffness under axial loads, excellent fire resistance as the rod is protected by the wood substance and good aesthetic appearance [3, 4].

Several configurations of these joints and design details for steel bonded-in rods can be found in the literatures and industry publications [2, 3, 5-10]. They are also employed to repair the rotted beam ends in traditional buildings [9] and, recently, the effect of adding the nanoparticles on the performance of epoxy resin when in situ repairing of members is needed has been reported [11].

As an alternative to steel rods, glass fibre reinforced plastic (GFRP) rods were also evaluated in UK [12] at the University of Bath between 1998 and 2001. Compared with steel rods, GFRP pultruded rods have more compatibility with resin and timber, higher resistance to humid or acid environments and improved performance due to better bonding and reduced weight. It was found that the most suitable resin for the bonding of rods into wood was epoxy resin. Ansell and Smedley [13] have described bonded-in technology for structural timber in which the advantages and performance of GFRP rods and epoxy resins are discussed.

Many studies [2, 3, 6-8, 10, 12-18] have identified factors that could affect the ultimate strength of glued-in (steel or GFRP) rod connections, including geometrical and mechanical parameters, environmental conditions, and load duration.

The primary recommendation for glue-line thickness in GFRP rods was 2mm, however a later study [19] revealed that epoxy resin is subject to a stress rate effect (SRE) under loading. This study showed that: 1) Instantaneous failure started sooner in the thicker glue-lines as the rate of loading was increased, 2) The dominant failure in thinner glue-line (0.5mm) was failure in the timber and 3) Failure modes changed with increased rate of loading and thicker glue-lines were more sensitive to change in loading rate. They concluded that that the glue-line thickness is an important parameter in determining fatigue life under dynamic loading. More recent research has shown that when bonding FRP materials to timber thinner epoxy resin glue-lines have adequate strength [20]. Other studies have shown that rate of loading effects in steel dowels bonded into timber are similar to duration of load effects [21, 22].

A few published papers analyse the strain and stress distribution along the anchorage using finite element methods [8, 18, 23]. However, the authors could not access any published work on modeling the rate of loading in epoxy resin. This paper uses finite element analysis (FEA) in order to understand the results of experimental work conducted by Madhoushi and Ansell in 2004 [19], including the effect of glueline thickness and rate of loading on stress transfer.

2. Materials and methods

ANSYS Software was used for this study. It should be noted that in 3D modelling of this connection the following issues were considered: 1) To model three different materials with different elastic properties, 2) The configuration of materials used in the model consist of a timber cube, cylindrical rod and hollow-cylindrical glue-line, and 3) Two interfaces between the rod and adhesive and the adhesive and timber.

In this work, the LVL and the GFRP materials were both assumed to be transversely isotropic, while the glue (adhesive) was assumed to be isotropic. The corresponding material values are given in Table 1. In order to obtain the stiffness parameters of materials the following issues were considered:

2.1. Stiffness parameters

2.1.1. LVL

1) Fig. 1 shows the stiffness directions in an element of LVL. In this model, the indices of L, R and T can be substituted for Z, Y and X, respectively. So:

$$E_L = E_Z \qquad E_R = E_Y \qquad E_T = E_X$$

$$G_{LR} = G_{ZY} \qquad G_{LT} = G_{ZX} \qquad G_{RT} = G_{YX} \tag{1}$$

$$\nu_{LR} = \nu_{ZY} \qquad \nu_{LT} = \nu_{ZX} \qquad \nu_{RT} = \nu_{YX}$$

2) LVL can be considered as a plane isotropic material in which the stiffness properties are the same in cross sections at the right angle to the grain direction [24]. Therefore, it can be said that:

$$G_{ZY} = G_{YZ} \qquad G_{ZX} = G_{XZ} \qquad G_{YX} = G_{XY}$$

$$\nu_{ZY} = \nu_{YZ} \qquad \nu_{ZX} = \nu_{XZ} \qquad \nu_{YX} = \nu_{XY} \tag{2}$$

3) The LVL model can be considered as solid timber without considering individual laminated veneers. So the properties of LVL should be close to the original wooden species used for veneer, namely spruce. Considering the general relationship between the elastic properties of softwoods in the major directions [24] the following properties result:

$$E_L = 11{,}000 \text{ MPa}, E_R = 894 \text{ MPa}, E_T = 552 \text{ MPa}$$

$$G_{LR} = 755.8 \text{ MPa}, G_{LT} = 708.8 \text{ MPa}, G_{RT} = 73.6 \text{ MPa} \tag{3}$$

$$\nu_{RT} = 0.47, \nu_{RL} = 0.041, \nu_{TL} = 0.033$$

However, since properties are isotropic over the cross section the average stiffness properties in the R and T direction were considered, as follows:

$$
\begin{aligned}
E_X &= E_Y = \frac{E_R + E_T}{2} \\
G_{YZ} &= G_{XZ} = \frac{G_{LR} + G_{LT}}{2} \\
\nu_{YZ} &= \nu_{XZ} = \frac{\nu_{RL} + \nu_{TL}}{2}
\end{aligned}
\qquad (4)
$$

2.1.2. GFRP rod

GFRP rod is an orthotropic material with the same properties E_X and E_Y in cross sections, as shown in Fig. 2. Values of some stiffness parameters have been found [12] as E_Z=45,000 MPa, G_{XZ} =G_{YZ} =14,000 MPa. Other values were recommended by Tufnol Ltd. who provided the GFRP rods for the study whereby E_X=9100 MPa, G_{XY}=1300 MPa and Poisson's ratios ν_{xy}.=0.25 and ν_{yz}=ν_{xz}=0.05.

2.2. Modelling procedure

Thanks to symmetry (in the YZ and XZ planes) only one quarter of the specimen (real system) had to be modelled. Finite element modelling was performed for four glue-line thicknesses of 0.5, 1, 2 and 4 mm. Other dimensions of model were considered as same as the real specimens [19].

In order to achieve meshing, the volume was swept to get a regular meshing pattern (Fig 3). An 8-node structural element, SOLID 185 in ANSYS, which is suitable for three dimensional (3D) modelling of solid structure solutions was selected. It has three degrees of freedom at each node, namely translations in the nodal X, Y, and Z directions. This element is suitable for materials with orthotropic properties. Pressures may be input as surface loads on the element faces as shown by the circled numbers on Fig 4. This element has the capability to be used on circular surfaces, for example at the rod-adhesive interface and the adhesive-timber interface. Also, the adherence at both interfaces (adhesive-timber and rod-adhesive) modelled using "Glue" procedure in ANSYS. It should be noted that other elements, which are suitable for *3D* structural analysis were also considered, but each of them had some limitations for utilization in this study, i.e regular meshing of circular surfaces. The number of created nodes was 21415 for 0.5, 1 and 2 mm glue-line thicknesses and 22119 for the 4 mm glue-line thickness. Also, the number of created elements was 19110 for 0.5, 1 and 2 mm glue-line thicknesses and 19740 for the 4 mm glue-line thickness.

After meshing, a tensile stress of 238.73 MPa (equal to a 12 kN tensile load) [19] was applied to the top surface of the rod. Constraints were applied on the lower surface of the model, only on the LVL, to react against the tension on the glued-in rod. Fig. 5 shows the applied tensile stress and constraints on the model.

2.3. Modelling procedure of the rate of loading effect

In order to model the experimental results of the rate of loading effect by FEA, it was assumed that: 1) Glue is a critical area of connection in timber jointed by GFRP bonded-in rods, 2) Glue-line thickness can be an important factor in determining strength in pull-out tests, 3) At higher rates of loading, the glue has an effective value of modulus of elasticity which is higher than the standard value and at a lower rate of loading the glue has a value of modulus of elasticity which is less than the standard value, because the glue is viscoelastic [25]. 4) Glue is an isotropic material and its shear modulus (G) is related to the elastic modulus (E) as follows:

$$G = \frac{E}{2(1+\nu)} \qquad (5)$$

FE models were created for 0.5 mm, 2 mm and 4 mm glueline thicknesses with a range of values of modulus of elasticity for epoxy resin, including 1/10, 1/5, 1/3, 1/2 times the standard values, modelling lower rates of loading, and 2, 3, 5 and 10 times the standard values, modelling higher rate of loading. Table 2 summarises the range of values of modulus of elasticity. These values are coded E_n in which n represents the factor of modulus of elasticity. For example, $E_{1/10}$ is the 1/10 of the standard value of modulus of elasticity, Es. The values of shear modulus, which are calculated using Eq. (5), are also summarized in Table 2.

3. Results and discussion

3.1. Effect of glue-line thickness

Fig. 6 shows the general FEA for four glue-line thicknesses for Z direction stresses. These figures show that the Z-direction stress distribution of timber joints using bonded-in GFRP rods is similar for 0.5, 1, 2 and 4 mm glue line thicknesses when the tensile stress is applied to the glue-in rod. The holographs of tensile stress in the Z direction for the rod, adhesive interface and the LVL are shown in Fig. 7 for a 0.5 mm glue-line and in Fig. 8 a 4 mm glue-line for comparison.

The results show that for several glue-line thicknesses, the distribution of Z-direction stresses are similar at the rod-adhesive interface. However, with increasing glue-line thickness the stress concentrations in the glue-line and consequently in LVL decline. These concentrated stresses are clearly shown in Fig. 9 for the shear stress (τ_{XZ}) for four glue-line thicknesses.

The trends in the distribution of shear stress (τ_{XZ}) from the centre of the rod to the LVL (Fig. 10) for four glue-line thicknesses show that the shear stress, after a small reduction at the centre of rod, starts to increase towards the rod-adhesive interface. Then, moving from the rod-adhesive interface towards the adhesive-timber interface the shear stress declines and this trend continues in the timber itself for all of the glue-line thicknesses. Fig. 11 shows this trend within the glue-line thicknesses. It can be seen that the shear stress of joints is maximum close to the rod-resin interface and declines towards the resin-timber interface.

The shear stress in the plane parallel to the axes of the joint (τ_{XZ} in Fig. 9) shows a similar trend for glue-line thicknesses. However, in an area close to the rod-adhesive interface its magnitude starts to increase and reaches an approximate maximum of 20-30% at the glue-line thickness away from the rod (Figs 10 and 11). This finding shows that the glue acts as a stress reducer in the connection and with increasing glue-line thickness we can expect a less severe stress in the glue itself and in turn in the timber. Hence, it can be said that the glue-line is an important factor in determining stresses close to glued-in GFRP rods.

3.2. Effect of rate of loading

Figs 12 to 14 plot the glue-line displacement parallel to the z axis versus distance from the centre of the rod for the three glue-line thicknesses as a function of the E values, which were used in modelling. These figures show clearly that the 0.5 mm glue-line has nearly the same displacement for several E values. However, the 2 mm glueline, and more so the 4 mm glue-line experience displacements changing much more with increasing E value. In other words, thick glue-lines are more sensitive to the rate of loading compared with thinner glue-lines.

Average vertical displacements for each of the E values are also plotted for three glueline thicknesses in Fig. 15. Again, it can be seen from this figure that the thin glueline thickness of 0.5 mm is less sensitive to change in E value. In contrast, the thicker glueline is more sensitive to change in E value.

The FEA results demonstrate that the thick glue-line of 4 mm is more sensitive to a change in E value than a thinner glue-line and it deforms more than a 2 mm or 0.5 mm glue-line thickness. Results demonstrate that for all resin E values and all glue-line thicknesses the translation D_Z remains almost constant close to the rod-adhesive interface, but as the glue line increases in thickness the displacement becomes increasingly more dependent on E value. Hence, rate of loading is expected to have a strong influence on deformation at the bonded-in rod interfaces. This finding proves that increasing the thickness of glue-line will result in joints which are more sensitive to rate of loading.

In the work of Madhoushi and Ansell [19] on the fatigue of rods bonded into timber 4 mm glue-line thickness failed instantly in fatigue, unlike thinner glue-lines. This seems to correlate with the smaller displacement of 4 mm glue-lines, shown in Figure 15 at the higher rates of loading. However, the displacement will still be bigger for the thinner glue-lines. Hence, the resin at the resin-rod interface will reach a critical strain and fail for 4 mm glue-line at higher rates of loading (similar to the fatigue loading) investigated by [19].

4. Conclusions

1. An FE model has been constructed for a glued-in GFRP rod in a block of LVL.
2. The distribution of Z direction stresses in LVL, resin and GFRP rod, when the rod is loaded in tension is quite similar for four glue-line thicknesses of 0.5, 1, 2 and 4 mm.
3. With an increasing thickness of glue-line, the concentration of Z-direction stresses declines across the glue-line thickness from the rod-adhesive interface towards the adhesive-timber interface.
4. The magnitude of shear stresses, σ_{XZ}, increase to a maximum within the glue-line in a zone about 20-30% into the resin layer and this is seen for all glue-line thicknesses.
5. The change of E values in the FE model to simulate rate of loading shows that thicker glue-lines are more sensitive to loading rate.

References

[1] Schreyer, A., Lam, F., Prion, H., Bathon, L.: Strength capacities and behavior of new composite timber-steel connector. Journal of Structural Engineering, 127, 888-893 (2001).

[2] Bainbridge, R., Mettem, C., Harvey, K., Ansell, M.: Bonded-in rod connections for timber structures-development of design methods and test observations. International Journal of Adhesion and Adhesives, 22, 47-59 (2002).

[3] Johansson, C.J.: Glued-in bolts, Centrum Hout, Almere, 1995.

[4] Serrano, E.: Glued-in rods for timber structures: An experimental study of softening behaviour. Materials and Structures, 34, 228-234 (2001).

[5] Buchanan, A.H., Fairweather, R.H.: Epoxied moment-resisting connections for timber buildings. Proceedings of Int. Workshop on Wood Connectors, 107-113 (1993).

[6] Bainbridge, R.J., Mettem, C.J.: A review of moment-resistant structural timber connections. Proc. Instn Civ. Engrs Structs & Bldgs, 128, 323-331 (1998).

[7] Bengtsson, C., Johansson, C.J.: Test methods for glued-in rods for timber structures. Proceedings of CIB-W18, Meeting 33, Delft, paper 33-7-8 (2000).

[8] Broughton, J.G., Hutchinson, A.R.: Pull-out behaviour of steel rods bonded into timber. Materials and Structures, 34, 100-9 (2001).

[9] Alam, P., Ansell, M.P., Smedley, D.: Mechanical repair of timber beams fractured in flexure using bonded-in reinforcements. Composites Part B: Engineering, 40, 95-106 (2009).

[10] Steiger, R., Gehri, E., Widmann, R.: Pull-out strength of axially loaded steel rods bonded in glulam parallel to the grain. Materials and Structures, 40, 69-78 (2007).

[11] Ahmad, Z., Ansell, M.P., Smedley, D.: Epoxy adhesives modified with nano- and micro-particles for in-situ timber bonding: Effect of microstructure on bond integrity. International Journal of Mechanical and Materials Engineering, 5, 59-67 (2010).

[12] Harvey, K., Ansell, M.P.: Improved timber connections using bonded-in GFRP rods. Proceedings of International Timber Engineering Conference, Vancouver, July-August, Poster 4 (200).

[13] Ansell, M.P., Smedley, D.: Briefing: Bonded-in technology for structural timber, Proceedings of the ICE - Construction Materials, 160, 95 –98 (2008).

[14] Bainbridge, R.J., Mettem, C.J., Harvey, K., Ansell, M.P.: Fatigue performance of bonded-in rods glulam using three adhesive types. Proceedings of CIB-W18, Meeting 33, Delft, 33-7-12 (2000).

[15] Rossignon, A., Espion, B.: Experimental assessment of the pull-out strength of single rods bonded in glulam parallel to the grain. Holz als Roh- und Werkstoff, 66, 419-432 (2008).

[16] Aicher, S., Dill-Langer, G.: Influence of moisture and load duration on performance of glued-in rods. RILEM Symposium on Joints in Timber Structures, Stuttgart, 383–392 (2001).

[17] Broughton, J.G., Hutchinson, A.R.: Adhesive systems for structural connections in timber. International Journal of Adhesion and Adhesives, 21, 177-186 (2001).

[18] Gardelle, V., Morlier P.: Geometric parameters which affect the short term resistance of an axially loaded glued-in rod. Materials and Structures, 40, 127-138 (2007).

[19] Madhoushi, M., Ansell, M.P.: Experimental study of static and fatigue strengths of pultruded GFRP rods bonded into LVL and glulam. International Journal of Adhesion and Adhesives, 24, 319-25 (2004).

[20] Raftery, G.M., Harte, A.M., Rodd, P.D.: Bonding of FRP materials to wood using thin epoxy gluelines. International Journal of Adhesion and Adhesives, 29, 580-588 (2009).

[21] Rosowsky, D., Reinhold, T.: Rate-of-load and duration-of-load effects for wood fasteners. Journal of Structural Engineering, 125, 719-724 (1999).

[22] Cousin, A., Salenikovich, A.: Rate of loading and moisture effects on dowel bearing strength. World Conference on Timber Engineering, Auckland, New Zealand, 2012.

[23] del Senno, M., Piazza, M., Tomasi, R.: Axial glued-in steel timber joints:experimental and numerical analysis. Holz als Roh- und Werkstoff, 62, 137-146 (2004).

[24] Bodig, J., Benjamin, A.J.: Mechanics of wood and wood composites. Van Nostrand Reinhold, 712 Pages, 1984.

[25] Callister, W.D., Rethwisch, D.G.: Materials Science and Engineering: An Introduction, John Wiley, 8th ed, 2010.

Figures Captions

Fig 1. Schematic diagram of stiffness directions in an element of LVL.

Fig 2. Schematic diagram of stiffness directions in a simple model of GFRP rod.

Fig 3. Regular meshing in one quarter of the real system for pull-out tests. (a) complete model of one fourth of system. (b) magnified view of interface between LVL and GFRP rod.

Fig 4. Geometry and node location of SOLID 185, 3-D 8-node structural solid.

Fig 5. Application of tensile stress and constraints on model in FE model of pull-out behaviour.

Fig 6. FE model of Z-direction stresses for four glue-line thicknesses.

Fig 7. FE model for tensile stress in the Z-direction for the rod, adhesive interface and the LVL for a 0.5 mm glue-line thickness.

Fig 8. FE model for tensile stress in the Z-direction for the rod, adhesive interface and the LVL for a 4 mm glue-line thickness.

Fig 9. FE model showing shear stress (τ_{XZ}) concentrations for four glue-line thicknesses where the bonded-in rod emerges from the surface of the LVL.

Fig 10. Distribution of shear stress (τ_{XZ}) across the section A for four glue-line thicknesses.

Fig 11. Distribution of shear stress (τ_{XZ}) within the glue-line thickness for four glue-line thicknesses.

Fig 12. FEA results showing the trends in vertical displacement of 0.5 mm thick glue-lines for several E values.

Fig 13. FEA results showing the trends in vertical displacement of 2 mm thick gluelines for several E values.

Fig 14. FEA results showing the trends in vertical displacement of 4 mm thick gluelines for several E values.

Fig 15. FEA results showing the trends in average vertical displacements for three glue-line thicknesses for nine E values.

Table Captions

Table 1. Elastic properties used in FEA (in MPa).

Table 2. Values of modulus of elasticity E (in MPa) and shear modulus G (in MPa) used in the FEA.

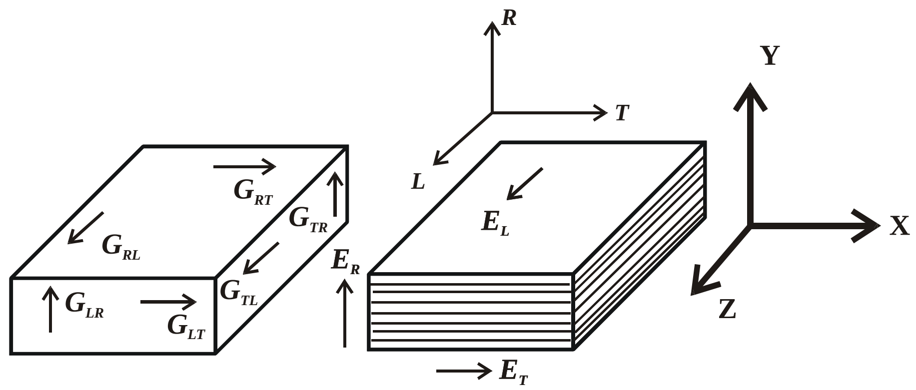

Fig 1. Schematic diagram of stiffness directions in an element of LVL.

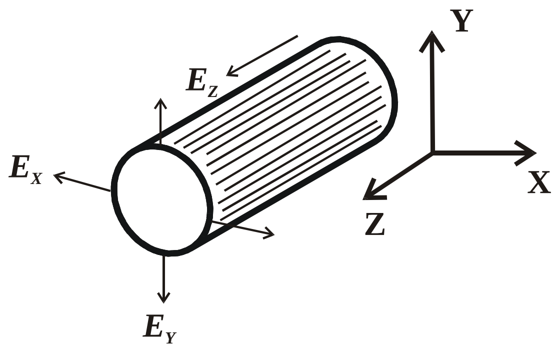

Fig 2. Schematic diagram of stiffness directions in a simple model of GFRP rod.

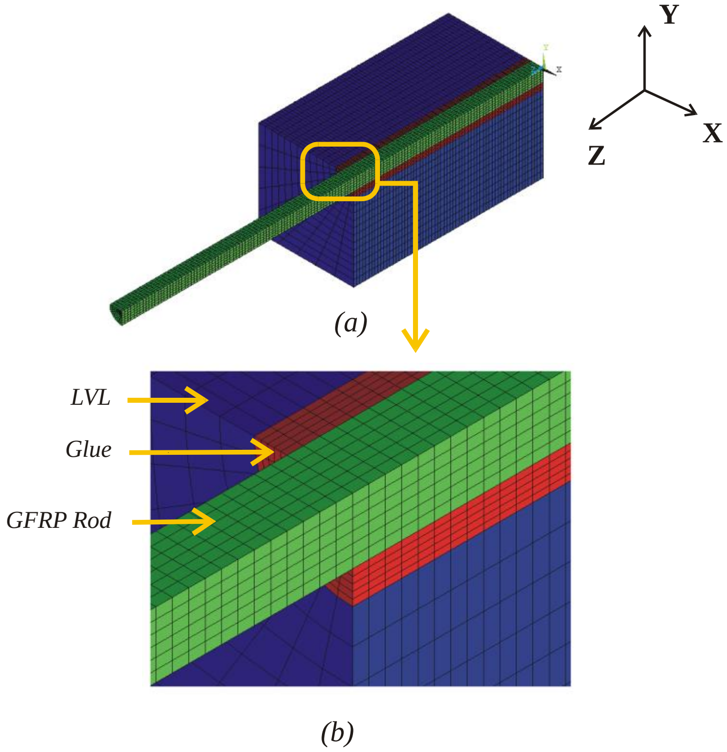

Fig 3. Regular meshing in one quarter of the real system for pull-out tests. (a) complete model of one fourth of system. (b) magnified view of interface between LVL and GFRP rod.

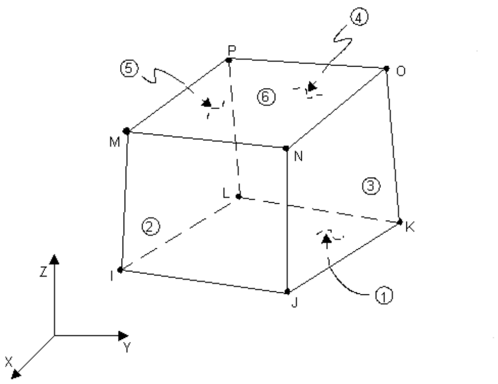

Fig 4. Geometry and node location of SOLID 185, 3-D 8-node structural solid.

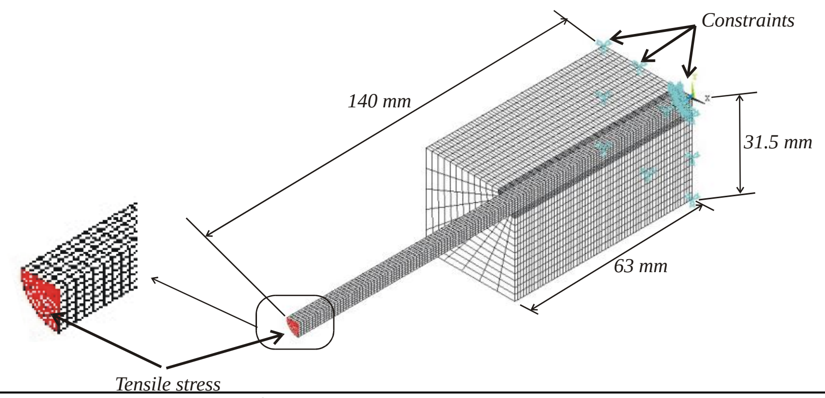

Fig 5. Application of tensile stress and constraints on model in FE model of pull-out behaviour.

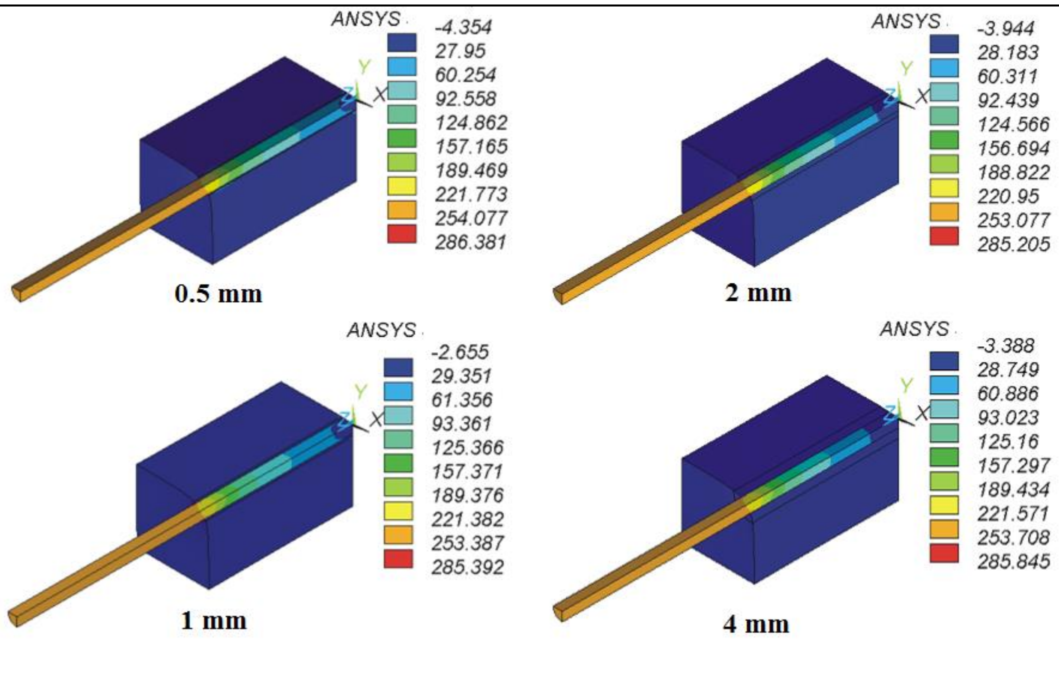

Fig 6. FE model of Z-direction stresses for four glue-line thicknesses.

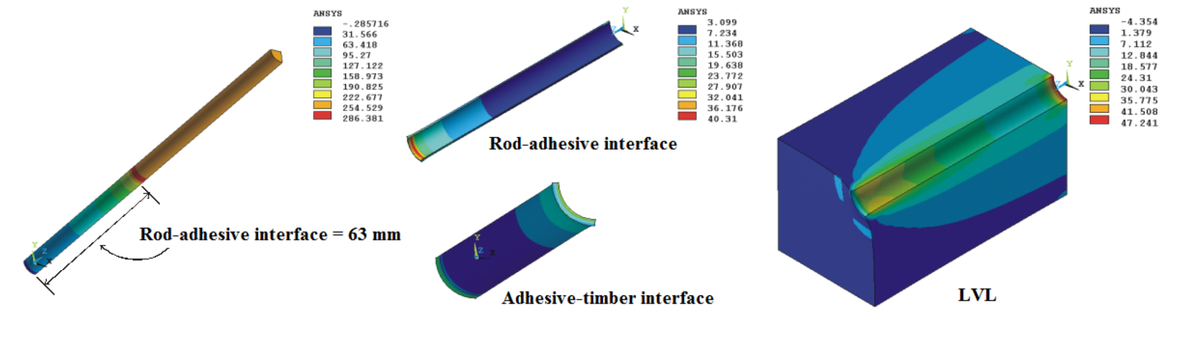

Fig 7. FE model for tensile stress in the Z-direction for the rod, adhesive interface and the LVL for a 0.5 mm glue-line thickness.

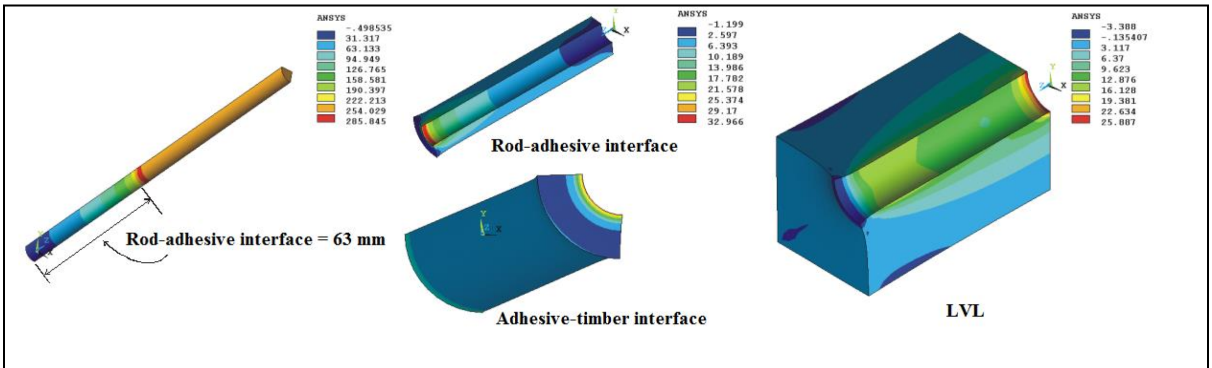

Fig 8. FE model for tensile stress in the Z-direction for the rod, adhesive interface and the LVL for a 4 mm glue-line thickness.

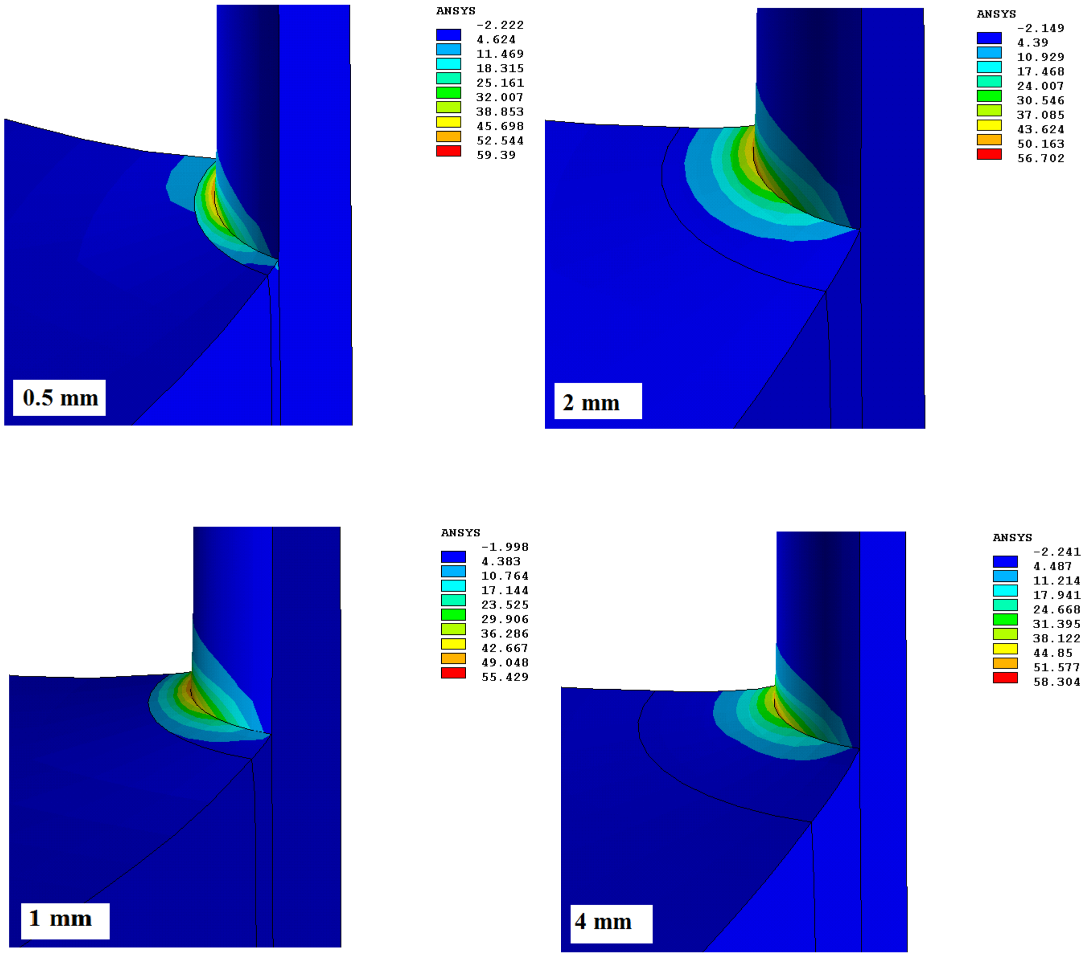

Fig 9. FE model showing shear stress (τ_{XZ}) concentrations for four glue-line thicknesses where the bonded-in rod emerges from the surface of the LVL.

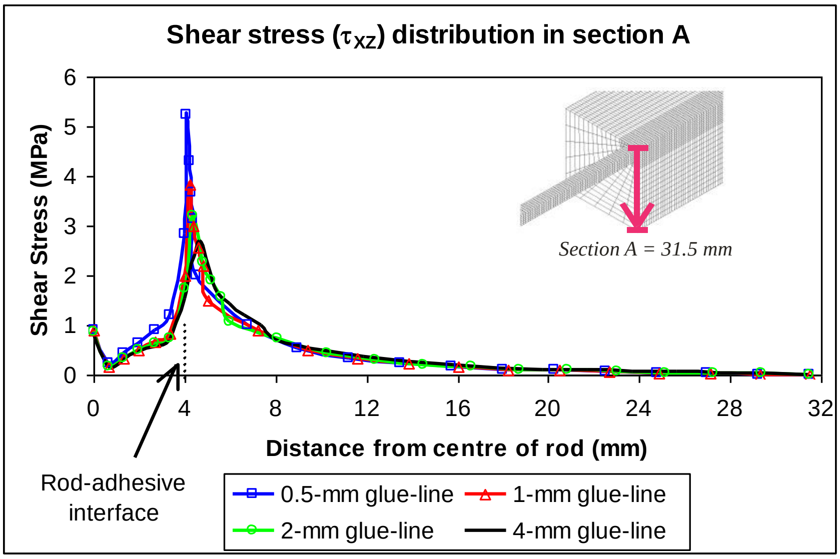

Fig 10. Distribution of shear stress (τ_{XZ}) across the section A for four glue-line thicknesses.

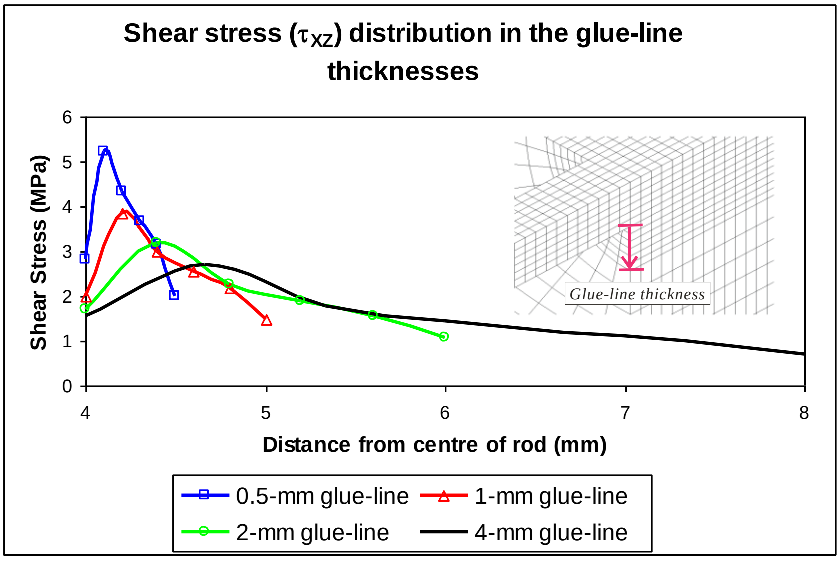

Fig 11. Distribution of shear stress (τ_{XZ}) within the glue-line thickness for four glue-line thicknesses.

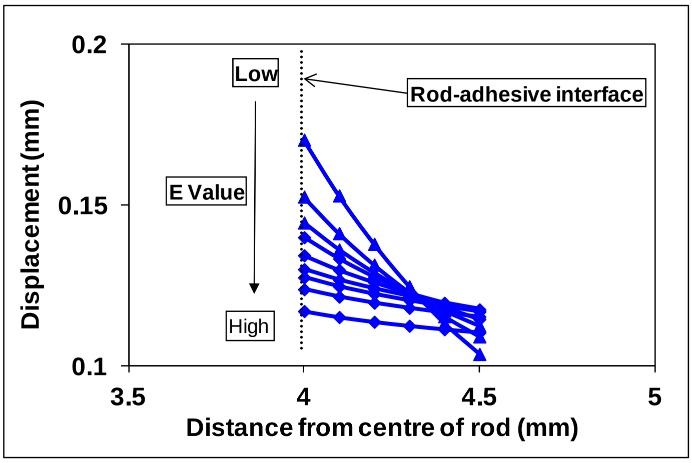

Fig 12. FEA results showing the trends in vertical displacement of 0.5 mm thick glue-lines for several E values.

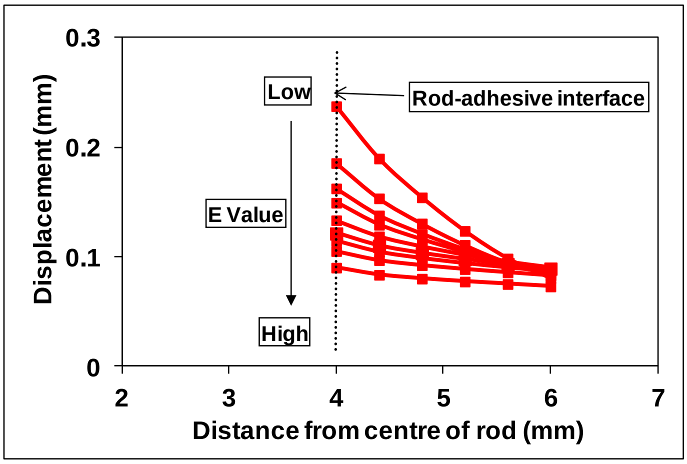

Fig 13. FEA results showing the trends in vertical displacement of 2 mm thick gluelines for several E values.

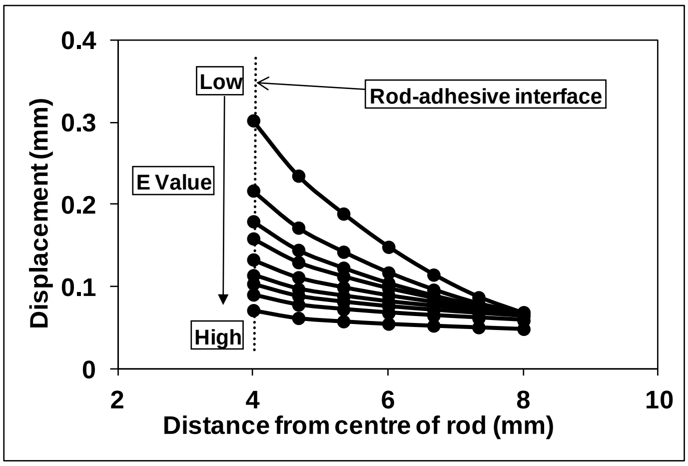

Fig 14. FEA results showing the trends in vertical displacement of 4 mm thick gluelines for several E values.

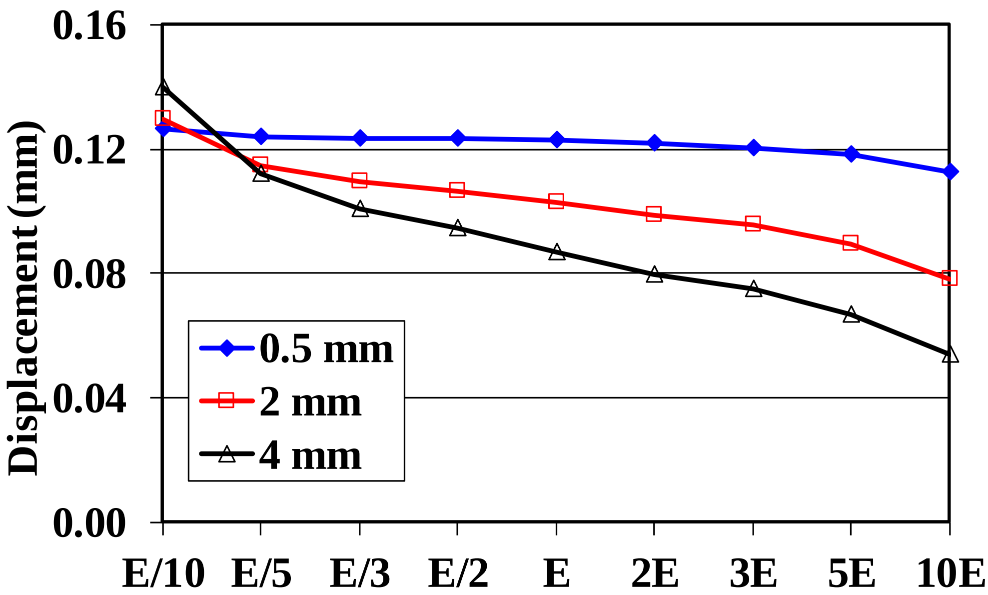

Fig 15. FEA results showing the trends in average vertical displacements for three glue-line thicknesses for nine E values.

Table 1. Elastic properties used in FEA (in MPa)*.

Materials	E_x	E_y	E_z	ν_{xy}	ν_{yz}	ν_{xz}	G_{xy}	G_{yz}	G_{xz}
LVL	732	732	11000	0.47	0.04	0.04	74	732.5	732.5
CB10TSS**	3500	3500	3500	0.3	0.3	0.3	1350	1350	1350
GFRP rod	9100	9100	45000	0.25	0.05	0.05	1300	14000	14000

* E: Elastic modulus, ν= Poisson's ration, G= shear modulus.

** Values recommended by Rotafix Ltd. It is considered as an isotropic material.

Table 2. Values of modulus of elasticity E (in MPa) and shear modulus G (in MPa) used in the FEA.

	$E_{1/10}$	$E_{1/5}$	$E_{1/3}$	$E_{1/2}$	E_S	E_2	E_3	E_5	E_{10}
E	350	700	1166.7	1750	3500	7000	10500	17500	35000
G	134.6	269.2	448.70	673.10	1350	2692.3	4038.5	6730.8	13462